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Natural convection in horizontal enclosures with multiple partitions

TATSUO NISHIMURA
Department of Chemical Engineering, Toyama University, Toyama 930, Japan

and

FUMIO NAGASAWA and YUJI KAWAMURA

Department of Chemical Engineering, Hiroshima University, Higashi-Hiroshima 724, Japan

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Abstract—Natural convection in horizontal enclosures with multiple partitions is experimentally studied for a wide range of Rayleigh numbers. A thin partition with a high conductivity is employed. The heat transfer rates, temperature distributions and flow visualizations reveal that natural convection in each cell constructed by the partitions is identical to the ordinary Benard problem, i.e. thermal coupling by conduction through partitions is minute. It is also found from an engineering standpoint that the horizontal and vertical enclosures are equivalent in the thermal insulation capability of partitions under the same conditions, in spite of different flow patterns.

1. INTRODUCTION

NATURAL convection in a fluid layer held between two parallel isothermal surfaces is important to many scientific and engineering disciplines. If the density gradient is normal to the gravitational acceleration vector, e.g. a differentially heated vertical enclosure, there will always be fluid motion. On the other hand, if the density gradient is parallel and opposite to the gravitational field, e.g. a horizontal enclosure heated from below, there is a critical density gradient below which no convection is possible. Several excellent reviews of the literature [1–3] have been published and there is no need to repeat them here.

The problem of primary interest in the literature is that of an enclosure with no partitions. However, in practical cases, multiple partitions are inserted into the enclosure to reduce heat losses by natural convection and thermal radiation. Heat transfer within enclosures containing partitions has been addressed in several investigations. Most of the studies dealt with heat transfer in a differentially heated vertical enclosure [4–12]. In particular, the present authors [12] proposed a boundary layer solution for multiple partitions and confirmed its validity by experiments.

On the other hand, there are very few studies for a horizontal enclosure heated from below. Recently Lienhard [13] predicted the Rayleigh–Benard stability limit for the multilayer situation interspersed with conductive partitions. However, heat transfer for the development of natural convection does not appear to have been studied previously, except for a single partition at low Rayleigh numbers [14]. Also Kamiuto [15, 16] studied theoretically the design criteria for multilayer systems, and he concluded that equal spacings of the partitions yield the minimum heat transfer rate. However, the validity of the assumptions included in the analysis is not confirmed. Namely, he assumed that the partitions are isothermal and that natural convection in each cell constructed by the partitions is identical to the ordinary Benard problem. Hereafter this analytical model is referred to as an isothermal partition model.

In this paper, natural convection in each cell constructed by multiple partitions equally spaced in a horizontal layer, as shown in Fig. 1, was experimentally studied for a wide range of Rayleigh numbers to confirm the validity of the isothermal partition model.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

Figure 2 shows a schematic diagram of the experimental apparatus. The main parts of the apparatus are the cooling part, the test section and the heating part. The test section consisted of a rectangular enclosure made of a lucite frame (20 mm thick) placed between two copper plates (12 mm thick) corresponding to the cold and hot walls. The following two kinds of enclosures were used in this study: the length and width of the enclosures were fixed (L = 300 mm and W = 200 mm) and the height was variable (H = 30 and 75 mm). The heating part consisted of the main heaters and the guard heaters mounted on the rear side of the main heaters across a bakelite plate. These heaters were divided into four parts to

NOMENCLATURE

- g gravitational acceleration
- H height of the enclosure
- H' height of the cell constructed by partitions
- Nu overall Nusselt number
- Nu_c cell Nusselt number
- L length of the enclosure
- N number of partitions
- Pr Prandtl number
- Ra overall Rayleigh number
- Ra_c cell Rayleigh number
- Q heat flux through the enclosure
- T temperature
- T_c temperature at the cold wall
- T_h temperature at the hot wall
- ΔT temperature difference, $T_h - T_c$
- $\Delta T'$ temperature difference across the cell
- W width of the enclosure
- z vertical coordinate.

Greek symbols

- α thermal diffusivity of fluid
- β volumetric expansion coefficient
- δ_t thickness of conduction layer
- η reducing rate of heat transfer defined by equation (9)
- θ dimensionless temperature, $(T - T_c)/(T_h - T_c)$
- λ thermal conductivity of fluid
- ν kinematic viscosity of fluid.

maintain a uniform temperature distribution on the hot wall. A cooling chamber was attached to the rear side of the cold wall, and the wall temperature was maintained uniform by introducing a sufficiently large amount of temperature-controlled brine from a refrigerator. The temperatures were measured by using 100 μm diameter copper–constantan thermocouples fixed at the positions shown in Fig. 2. In order to minimize the heat loss, the experimental apparatus was covered with polystyrene foam insulating material 60 mm thick and in addition the apparatus was located in a temperature-controlled room. The partition was made of a thin copper plate, 100 μm thick, which was the same as that used for vertical enclosures in the previous work [12]. The number of partitions was varied from 1 to 3. The working fluid was water. Experiments were carried out by changing the temperature difference between the hot and cold walls ($\Delta T = 3$–15 K). The experimental data were taken after the thermal and fluid-dynamic conditions had reached a steady state. It took approximately 7–12 h to reach steady-state conditions.

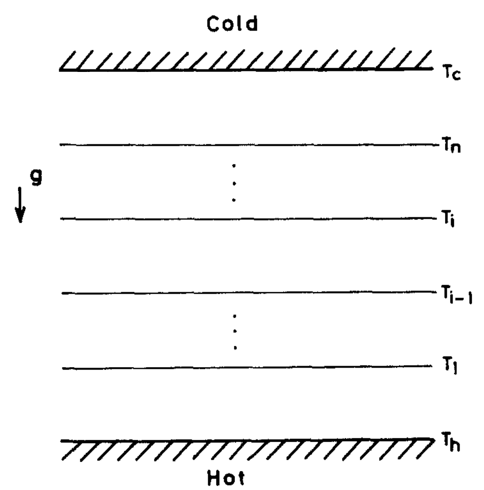

FIG. 1. Schematic diagram of a layer with partitions.

In addition, the flow in each cell divided by partitions was observed by the phenolphthalein method in order to understand the natural convection modes for this system. The details of this method have been described in the literature [17, 18]. Small quantities of phenolphthalein, sodium chloride and ethyl alcohol were added to distilled and degasified water, without significantly affecting the properties of water. Electric leads from a d.c. supply were connected to the ends of hot and cold walls and partitions made of a copper plate.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The heat transfer rate across the enclosure was measured electrically, monitoring the power dissipated in the main heaters (Fig. 2). The heat transfer measurements are presented in Fig. 3, where the overall Nusselt and Rayleigh numbers are defined as

$$Nu = QH/(\lambda \Delta T) \tag{1}$$

$$Ra = g\beta \Delta T H^3/(\nu\alpha). \tag{2}$$

The physical properties appearing in the above definitions have been evaluated at the end-to-end average temperature $0.5(T_h + T_c)$.

The Nusselt number for no partitions is in good agreement with the correlation of water by Hollands *et al.* [19], in spite of the values of the aspect ratio of the enclosure ($H/L = 4$ and 10). That is, horizontal enclosures have no effect on aspect ratio, contrary to vertical enclosures.

In the case of partition, the Nusselt number decreases drastically on increasing the number of partitions N, but the introduction of the partition does not produce a proportional reduction in heat transfer. The dotted lines also shown in this figure denote the

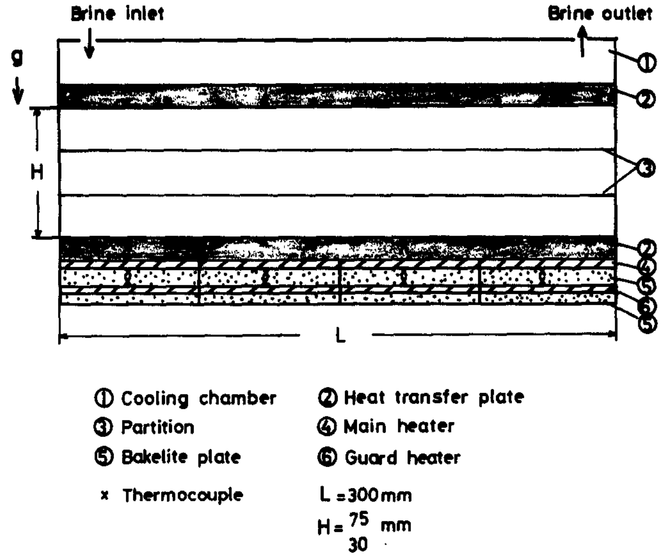

FIG. 2. Experimental apparatus.

heat transfer correlations estimated by the isothermal partition model described in Section 1. The model assumes that natural convection in each cell constructed by partitions occurs independently, i.e. it is identical to the ordinary Benard problem, and also neglects the effects of wall thickness and wall resistance in consideration of the experimental condition, e.g. a thin partition with a high conductivity. Also shown on the graph, the points marked by an arrow represent the critical Rayleigh number for the onset of convection by Lienhard [13]. The effects of wall thickness and conductance are considered in the calculation of the critical Rayleigh number. These critical values are slightly smaller than those estimated by the isothermal partition model, indicating a thermal coupling by conduction through partitions. However, after the onset of convection, the experimental data agree with the heat transfer correlations by the isothermal partition model for any value of N. It is confirmed that the thermal coupling is minute in the range of high Rayleigh numbers for this system.

A re-plot of Fig. 3 appears in Fig. 4, which depicts the relationship between cell Nusselt and Rayleigh numbers. These numbers are defined as follows:

$$Nu_c = QH'/(\lambda \Delta T') \quad (3)$$

$$Ra_c = g\beta \Delta T' H'^3/(\nu\alpha). \quad (4)$$

By confirmation of the isothermal partition model, the temperature difference across the cell constructed by the partitions $\Delta T'$ and the height of the cell H' are given as

$$\Delta T' = \Delta T/(N+1) \quad (5)$$

$$H' = H/(N+1). \quad (6)$$

All data almost lie on the heat transfer correlation for no partition in a wider range of Rayleigh numbers. The change in the flow pattern accompanying a variation of Rayleigh number for a water layer with no partition is also shown on this figure. These flow patterns were previously observed by Krishnamurti [20]. This experimental range belongs to regions B, C and

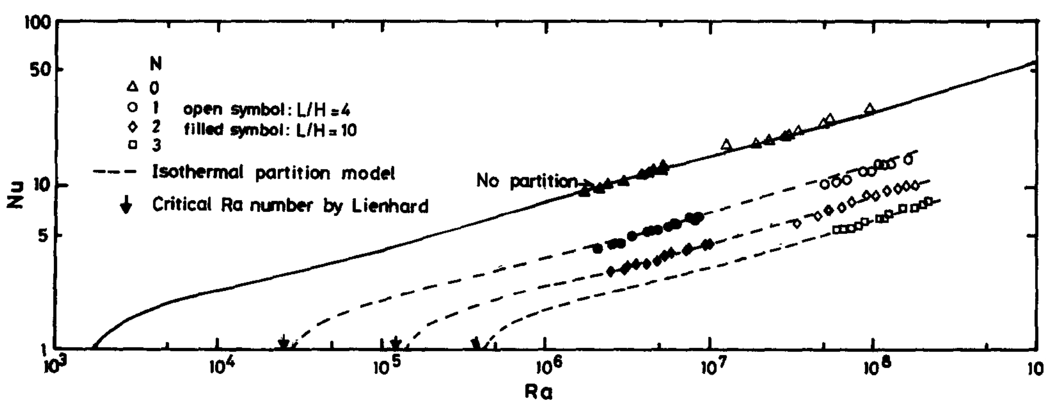

FIG. 3. Nusselt number vs Rayleigh number.

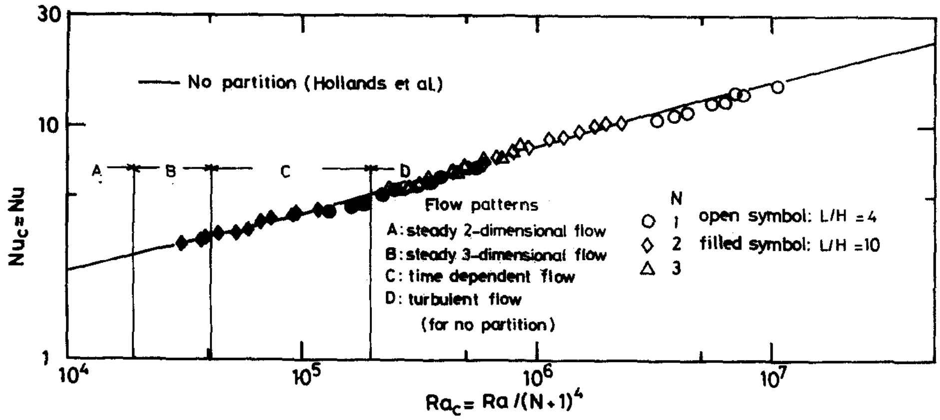

FIG. 4. Cell Nusselt number vs cell Rayleigh number.

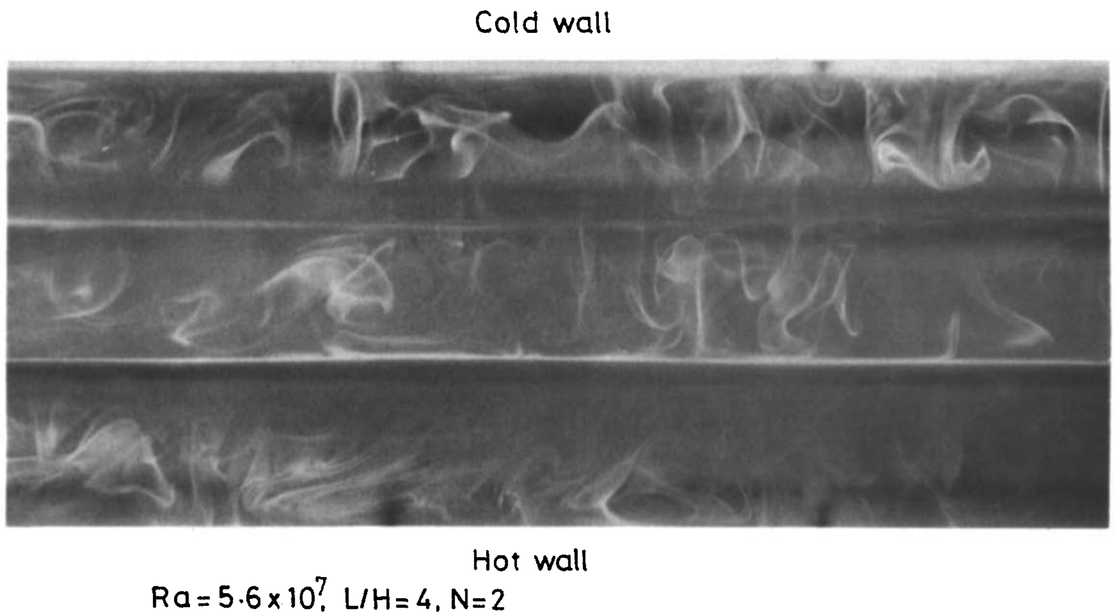

FIG. 5. Sample photograph of the turbulent flow by the phenolphthalein method.

D which correspond to a steady three-dimensional flow, time-dependent flow and turbulent flow, respectively. In order to confirm this, the flow pattern for the case of partition was observed by the phenolphthalein method. Flow visualizations showed that the flow patterns in this experimental range change from steady three-dimensional flow to turbulent flow. Thus the flow pattern in each cell is identical to that for the case of no partition, as well as the heat transfer rate. For example, the photograph of the flow pattern for turbulent flow is shown in Fig. 5. Thermals appear at random in each cell.

Figure 6 shows a mean temperature distribution across the enclosure for the case of turbulent flow. The solid line represents the temperature distribution estimated by both the isothermal partition model as mentioned above and the conduction layer model by Hollands *et al.* [19] who considered the heat transfer to be conducted through a layer of stagnant fluid near

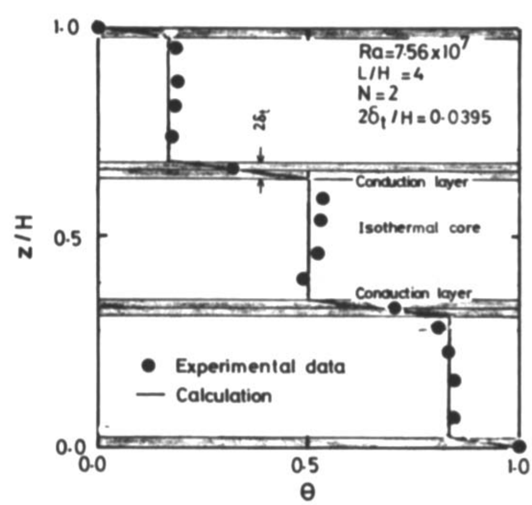

FIG. 6. Vertical temperature profile.

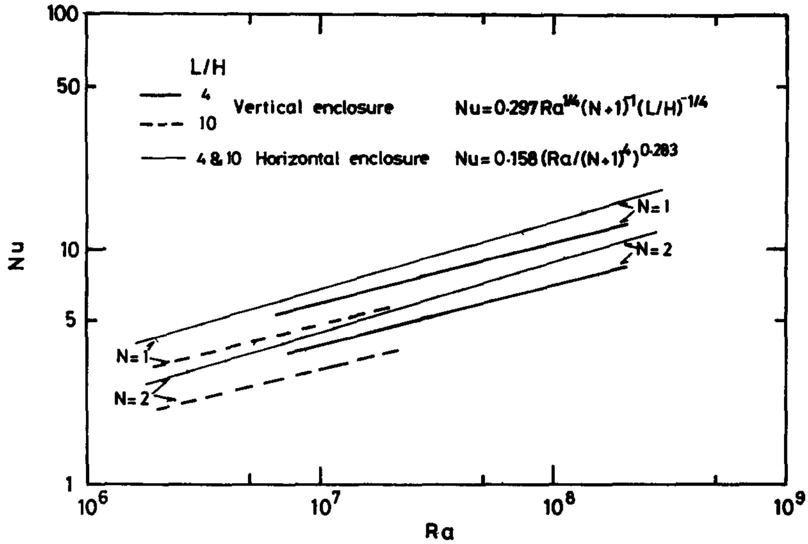

FIG. 7. Comparison of vertical and horizontal enclosures in Nusselt number.

the walls (called the conduction layer). The thickness of the conduction layer δ_t is estimated from the Nusselt number. For this experimental condition, $2\delta_t/H$ has a value of 0.0395. Experimental data measured by thermocouples inserted into the enclosure satisfactorily agree with the solid line, as expected from the results of heat transfer rates and flow visualizations. It should be noted that instantaneous signals of the thermocouples are fluctuating with a long period, e.g. of the order of 15–30 s, because of the thermals.

4. COMPARISON OF HORIZONTAL AND VERTICAL ENCLOSURES

Next we compare horizontal enclosures with vertical enclosures in heat transfer under the same conditions. The heat transfer correlation for vertical enclosures has previously been obtained in a laminar boundary layer flow region [12]. The following correlation is recommended:

$$Nu = 0.297Ra^{1/4}(N+1)^{-1}(L/H)^{-1/4}. \quad (7)$$

On the other hand, the heat transfer correlation for horizontal enclosures is obtained from the correlation with no partitions. Because the isothermal partition model is available for this system, contrary to the vertical enclosure. Thus the heat transfer correlation is given by the relationship of Fig. 4 in this experimental range as follows:

$$Nu = 0.158[Ra/(N+1)^4]^{0.283}. \quad (8)$$

Figure 7 shows a comparison of the horizontal and vertical enclosures in heat transfer. On the whole, the heat transfer rate for the horizontal enclosure is larger than that for the vertical enclosure, and the tendency becomes remarkable for a higher aspect ratio. This difference is due to the flow patterns. That is, the flow pattern for the vertical enclosure is a type of laminar boundary layer along the walls or the partitions, while the flow pattern for the horizontal enclosure belongs to turbulent flow in which the heat is transported primarily by the thermals.

Returning to the engineering application which motivated this fundamental study, we now assess the thermal insulation capability of the multiple partitions. The reducing rate of heat transfer η is defined as

$$\eta = 1 - Nu_p/Nu_0 \quad (9)$$

where Nu_p is the Nusselt number with partitions and Nu_0 is the Nusselt number without partitions.

Using equation (8), η for the horizontal enclosure is obtained as

$$\eta = 1 - 1/(N+1)^{1.18}. \quad (10)$$

The value of η for the vertical enclosure has been given in the previous study [12].

Figure 8 shows a comparison of the vertical and

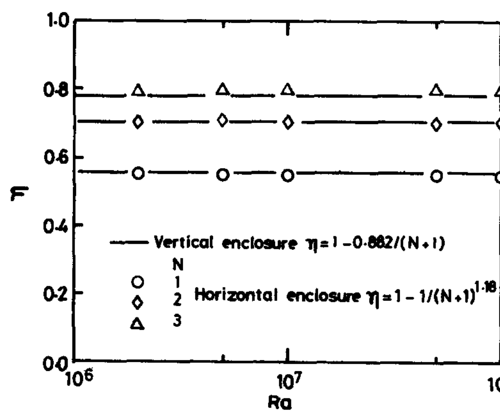

FIG. 8. Heat transfer reduction due to the presence of partitions.

horizontal enclosures in η. Although the relationship of η is different between the vertical and horizontal enclosures as expected from a comparison of heat transfer correlations of Fig. 7, the value of η is almost identical for both enclosures. Thus it is found that the horizontal and vertical enclosures are equivalent in the thermal insulation capability of partitions from an engineering standpoint.

5. CONCLUSIONS

Natural convection heat transfer in horizontal enclosures with multiple partitions was investigated experimentally. The enclosure was bounded by isothermal horizontal walls at different temperatures and adiabatic vertical walls. A thin partition with a high conductivity was employed and the partitions were equally spaced in the enclosure.

(1) The measurements of heat transfer rates and temperature distributions and flow visualizations reveal that natural convection in each cell is identical to the ordinary Benard problem.

(2) The horizontal and vertical enclosures are almost equivalent in the thermal insulation capability of partitions, in spite of different flow patterns.

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CONVECTION NATURELLE DANS DES CAVITES HORIZONTALES AVEC PLUSIEURS CLOISONS

Résumé—On étudie expérimentalement la convection naturelle dans des cavités horizontales avec plusieurs cloisons, pour un large domaine de nombre de Rayleigh. On emploie une fine cloison à haute conductivité. Les flux thermiques, les distributions de température et les visualisations d'écoulement montrent que la convection naturelle dans chaque cellules formée par les cloisons est indentique au problème ordinaire de Bénard, avec faible couplage thermique par conduction à travers les cloisons. On trouve aussi, du point de vue de l'ingénieur, que les cavités horizontales et verticales sont équivalentes, du point de vue de la capacité d'isolation thermique, en dépit des différentes configurations d'écoulement.

NATÜRLICHE KONVEKTION IN HORIZONTALEN HOHLRÄUMEN MIT MEHRFACHER UNTERTEILUNG

Zusammenfassung—Für einen weiten Bereich der Rayleigh-Zahl wurde die natürliche Konvektion in horizontalen Hohlräumen mit mehrfacher Unterteilung experimentell untersucht. Dabei werden dünne Trennbleche mit hoher Leitfähigkeit verwendet. Die übertragene Wärme sowie die Temperaturverteilungen und Strömungsbilder zeigen, daß die natürliche Konvektion in allen von den Teilungen erzeugten Zellen mit dem gewöhnlichen Bénard-Problem identisch ist, d.h. die thermische Ankopplung durch Wärmeleitung in den Trennblechen ist sehr gering. Für die praktische Anwendung wurde außerdem erkannt, daß horizontale und vertikale Hohlräume bei gleichen Bedingungen in ihrer Wärmedämmwirkung gleich sind—trotz unterschiedlicher Strömungsmuster.

ЕСТЕСТВЕННАЯ КОНВЕКЦИЯ В ГОРИЗОНТАЛЬНО ВЫТЯНУТЫХ ПОЛОСТЯХ С БОЛЬШИМ КОЛИЧЕСТВОМ ПЕРЕГОРОДОК

Аннотация—Экспериментально исследуется естественная конвекция в горизонтально вытянутых полостях с большим количеством перегородок в широком диапазоне значений числа Рэлея. Используются тонкие перегородки с высокой теплопроводностью. Полученные значения коэффициента теплопереноса, распределения температур и визуальные наблюдения за течением показывают, что естественная конвекция в каждой из образованных перегородками ячейке представляет собой обычную конвекцию Бенара, т.е. влияние передачи теплоты через перегородки незначительно. С практической точки зрения перегородки в горизонтальных и вертикальных полостях в одинаковых условиях создают одинаковый теплоизолирующий эффект несмотря на различный характер течения в этих полостях.